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Research Article

Influence of Steatite and Fly Ash on the Fresh-Hardened Properties and Micromorphology of Self-Compacting Concrete

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This experimental study investigates the effect of steatite and fly ash on the fresh and hardened properties of self-compacting concrete (SCC). Accordingly, ordinary Portland cement (53 grade) was replaced with various fractions of fly ash (10% and 20%) and with various percentages (5%, 10%, 15%, 20%, and 25%) of steatite by weight of cement as a filling material. European guidelines for self-compacting concrete guidelines were adopted for producing SCC. The fresh concrete properties were studied using the slump flow test, T_{500} test, L-box test, and V-funnel test, whereas the hardened properties of SCC were studied by the cube compression test, splitting tensile strength test, and flexural strength test on various days (7 days, 14 days, 28 days, and 90 days). In addition to that, microstructural studies were carried out to justify the hardened concrete results. The result shows that the steatite content reduces the flow properties of concrete, whereas the fly ash content increases the flow properties. In terms of strength, addition of fly ash enhanced the later age strength, whereas up to 15% of replacement with steatite improved the compressive, tensile, and flexural strength, beyond which there is a fall in the strength parameters which is however higher than the control specimen.

1. Introduction

The strength of concrete is governed by many factors such as water cement ratio, incorporation of mineral and chemical admixtures, proper mixing, compaction, and curing. Amidst one of the key factors is removal of voids in concrete and there by preparing a densified concrete, which can be achieved by introducing finer particles and proper compaction. Fly ash (FA) and ultra-fine natural steatite powder (UFNSP) are finer particles than cement, replacing cement with FA producing less permeable and denser concrete; addition on UFNSP also has the same effect in concrete. Due to evolution over years, the conventional concrete is outdated and replaced with special concretes in all the construction industries. Depending upon the placing and the functional requirements, these special concretes were preferred.

SCC was a special concrete developed at Japan in 1980s [1]. This concrete has good passing ability, filling ability, and good segregation resistance which makes this type of concrete be used in heavily reinforced areas such as beam column joints, and deep formwork like columns, shear wall, and foundation. Because of its highly flowable nature, this concrete is highly pumpable too with no need of external compaction [2–12]. Thus, it reduces the human efforts; henceforth, the construction cost also got reduced [13]. Based on the earlier literatures, we can clearly understand that, for producing SCC more cement content is needed, this leads to more CO_2 emission that reflects in global warming [14, 15]. In order to minimize this, supplementary cementitious material is a mandatory one for SCC. Hence, in this present study, FA and UFNSP were chosen to improve the SCC properties.

Fly ash being a byproduct, when introduced in concrete, increases the flow properties of fresh concrete, henceforth reducing the superplasticizer dosage. However, the initial strength of concrete will be comparatively lower than conventional concrete [16–18], whereas there will be increase in later age strength and durability properties of concrete. It also indulges in minimizing the initial cracks due to plastic shrinkage by reducing the heat of hydration [19]. Adding FA reduces the chloride penetration and prevents the reinforcement from corrosion in reinforced cement concrete structures [20].

Steatite, the hydrated form of magnesium silicate, is a type of metamorphic rock with hardness index of one which enables us to archive the powder form easily. Since steatite is rich in magnesium with no pozzolanic requirements, it acts as a filling material in concrete thus increasing the water demand consequently reducing the flow properties of SCC. The fine particle size enables the steatite powder to fill the fine voids and increases the strength and durability properties up to a certain extent. It has been noticed that adding mineral admixtures such as FA and steatite not only improves the property but also reduces the cost of the concrete mix [20–23]. Based on the earlier literatures, it was also noted that for producing SCC chemical admixtures like super plasticizer (SP) and viscous modifying agent (VMA) are required [21–25]. Adding SP increases the flow and adding VMA makes the concrete more resistant to segregation effects.

2. Research Significance

So far research in SCC with FA, GGBS, silica fume, marble powder, and limestone filler are plenty whereas SCC with other mineral admixtures (steatite and FA) do not have adequate attention. Hence, in this study SCC with steatite and FA were considered [26–29].

Based on the earlier literatures, they clearly state that adding steatite increases the water demand [30, 31] and hence it reduces the flow properties, and it increases the strength properties up to a certain limit [32, 33]. Addition of fly ash enhances the workability and fluidity owing to its spherical particle shape. It also increases the long-term strength by its pozzolanic reaction. So, an attempt is made to overcome the reduction in flow when adding steatite by adding FA and produce a high strength and flowable SCC. For this purpose, SCC is developed with binary and ternary systems of Portland cement, fly ash (FA) along with ultrafine natural Steatite powder (UFNSP). FA is included as pozzolanic material with 10% and 20% whereas steatite is introduced as filling material with 5%, 10%, 15%, 20%, and 25% by weight of cement. Fresh concrete properties were studied using slump flow, T_{500} test, L-box test, and V-funnel test whereas the harden properties of SCC were studied by cube compression test, splitting tensile strength test and flexural strength on various days (7 days, 14 days, 28 days, and 90 days). Finally, microstructural studies were carried out by SEM analysis to support the justification of hardened concrete results.

3. Experimental Study

3.1. Materials. To produce self-compacting concrete ordinary Portland cement of 53 grade conforming to the requirements specified in IS-12269 [34] with the specific gravity of 3.15, ultrafine natural steatite powder (major components 62% SiO_2, 33% MgO) with the specific gravity of 2.55 and Class F fly-ash with the specific gravity of 2.25 were included as powder material. Coarse aggregate of specific gravity 2.7 with the particle size of 10 mm to 12.5 mm was used. M-sand was used as the fine aggregate. The specific gravity of M-sand was found to be 2.65 with the fineness modulus of 2.62 conforming IS 383-1970 [35]. Chemical admixtures such as polycarboxylate based water, reducing admixture high end superplasticizer (CERA HYPERPLAST XR-W40) and viscosity modifier, and Master matrix VMA 362 were used to maintain the workability. Potable water was used for mixing and curing process.

3.2. Mixture Design. To generate SCC, ordinary Portland cement of 53 grade conforming to the requirements specified in IS-12269, class F fly ash from Kudankulam Nuclear Power Station India, and UFNSP purchased from local distributor in Madurai, Tamil Nadu, India, were used as powder materials in this study. And for FA, M-sand with fineness modulus of 2.6 and specific gravity of 2.67 was used, whereas, for CA, angular aggregate with the specific gravity of 2.72 was used throughout the study.

For SCC, mix is produced using trial and error method as specified in the European guidelines for self-compacting concrete specification [36] (Table 1) with the cement content of 530 kg/m^3 in which cement is replaced with 10 and 20% of fly-ash. Steatite is taken in various ratios like 5%, 10%, 15%, 20%, and 25% to the weight of cementitious material and is included as an additive in this study. Twelve SCC mixes were produced as mentioned below. The detailed mix proportions are presented in Table 2. In Mix ID SCC0FA10 represents self-compacting concrete with 0% steatite and FA10 represent 10% fly ash has been replaced with cement; for example, SCC10FA20 indicates mix in which 20% fly-ash is replaced with cement and 10% steatite is added as additive to that mix.

To control the mix proportions and to produce homogeneous self-compacting concrete, the mixing method suggested by Khayat et al. [9] was adopted throughout this study. Based on that, the mixing sequence and the duration were as follows.

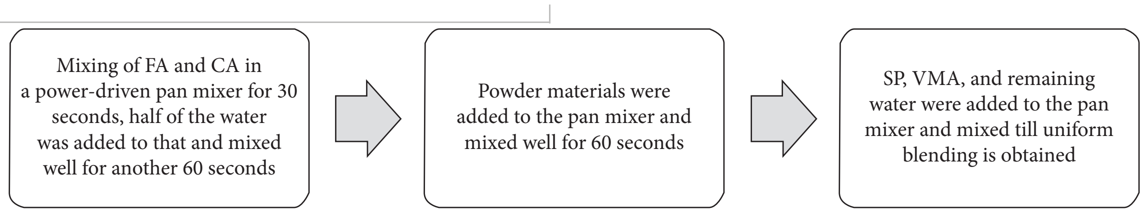

Table 1: Trial and error method to obtain SCC.

Trial	Mix ratio	Identified fault	Implemented action to eradicate the fault according to European guidelines (as per Table C.2)
1	1 : 1.52 : 1.52 with -w/b ratio of 0.48	Rapid loss of workability	Use different superplasticizer, use slower reacting cement type
2	1 : 1.52 : 1.52 with w/b ratio of 0.48	Segregation	Increase the mortar volume, reduce the water content
3	1 : 1.52 : 1.48 with w/b ratio of 0.4	Viscosity too high	Increase the water content
4	1 : 1.52 : 1.48 with w/b ratio of 0.43	Nil	—

Table 2: Mix proportions developed to achieve SCC.

Mix ID	Cement (kg/m^3)	Fly ash (kg/m^3)	Steatite (kg/m^3)	Water (lit/m^3)	SP (kg/m^3)	VMA (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)
SCC0FA10	477	53	0	227.9	10.6	2.12	805.6	784.4
SCC5FA10	477	53	26.5	239.3	11.13	2.22	805.6	784.4
SCC10FA10	477	53	53	250.7	11.66	2.33	805.6	784.4
SCC15FA10	477	53	79.5	262	12.19	2.44	805.6	784.4
SCC20FA10	477	53	106	273.5	12.72	2.54	805.6	784.4
SCC25FA10	477	53	129.5	283.6	13.19	2.64	805.6	784.4
SCC0FA20	424	106	0	227.9	10.6	2.12	805.6	784.4
SCC5FA20	424	106	26.5	239.3	11.13	2.22	805.6	784.4
SCC10FA20	424	106	53	250.7	11.66	2.33	805.6	784.4
SCC15FA20	424	106	79.5	262	12.19	2.44	805.6	784.4
SCC20FA20	424	106	106	273.5	12.72	2.54	805.6	784.4
SCC25FA20	424	106	129.5	283.6	13.19	2.64	805.6	784.4

4. Results and Discussion

4.1. Fresh Properties of SCC. The fresh concrete was tested for its flow properties by slump flow test, T_{500} test, V-funnel test, and L-box test. The results thus obtained for the fresh concrete are discussed in the following section as follows.

4.1.1. Slump Test. Slump values were observed to be influential ranging from 645 mm to 760 mm (Figure 1) for the mixes with various steatite % (5, 10, 15, 20, and 25) and fly ash % (10 and 20). Except the mix SCC25FA10 and SCC0 FA20 remaining, all other mixes come under SF2 class; hence, it is utilized for normal applications like walls and columns, whereas the mix SCC0FA20 was categorized as SF3 and this is used in vertically congested places and structures with more complex shapes. This mix will have better surface finish compared to all others.

4.1.2. T500 Test. The T_{500} test resulted in values (Figure 2) from 2 seconds to 5 seconds for the same series of mixes representing an average yield value and viscosity that makes it apt for the SCC. Other than the mix ID SCC0FA20 remaining, all were classified as VS 2; hence, this has more resistance to segregation effects. Increasing flow time results in thixotropic effect and this will be helpful in limiting the formwork pressure.

4.1.3. V-Funnel Test. The test result clearly shows that addition of steatite increases the flow timing; at the same time, this effect was compensated by addition of fly ash. Hence, the combination of max fly ash content and minimum steatite content has less flow timing and fall under VF1 category. The V-funnel test results (Figure 3) were within the promising limits, whereas SCC20FA10 and SCC25FA20 developed much flexible results indicating good filling ability with no blockage in it.

4.1.4. L-Box Ratio Test. Almost all the concrete mixes showed up with a blocking ratio approximating the value 1 (Figure 4), which infers the better passing ability of the mixes along with the viscosity and yield values within the limit.

4.2. Hardened Properties of SCC

4.2.1. Compressive Strength. The SCC specimens were tested for compressive strength at 7 days, 14 days, 28 days, and 90 days. The strength attainments (Figures 5 and 6) of the specimens were notably higher in the later ages of concrete than the early age strength owing to the addition of fly ash in the concrete mix. The attained strength at 90 days were 8.74%, 32.43%, 75.26%, 107.05%, 78.28%, and 33.44% higher for SCC0FA10, SCC5FA10, SCC10FA10, SCC15FA10, SCC20FA10, and SCC25FA10, respectively. The SCC15FA10 specimen showed notably higher % of increase in the strength after which the rise was noted to have a sudden fall indicating the addition of steatite after 15% of the weight to cease the compressive strength of the concrete specimens whereas enormous strength gain is noted at 90 days for the test samples with 90.07%, 81.60%, 94.20%, 95.40%, 93.23%, and 118.47% for SCC0FA10, SCC5FA10, SCC10FA10, SCC15FA10, SCC20FA10, and SCC25FA10, respectively, when compared with 7-day strength. The specimens of SCC25FA10 were noted to showcase maximum gain in compressive strength of 118.47% higher on the later age (90 days). Coming to the 28 days strength of the specimens, SCC15FA10 were noted to develop 91.48% higher compressive strength than the designed strength, whereas SCC0FA10 mix

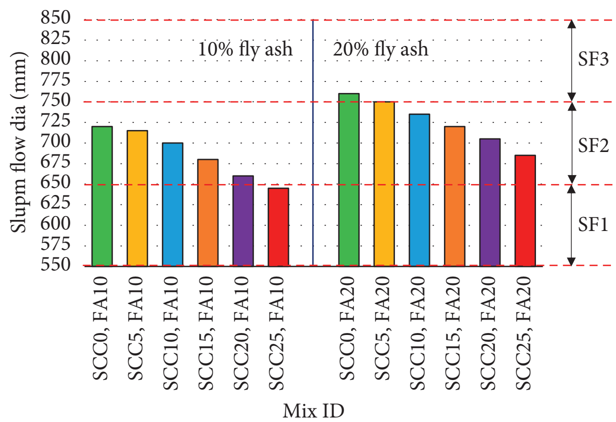

FIGURE 1: Slump values for the fresh concrete.

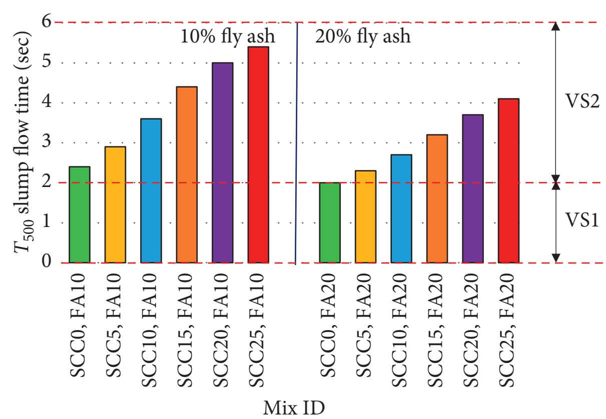

FIGURE 2: T_{500} slump flow values for the fresh concrete.

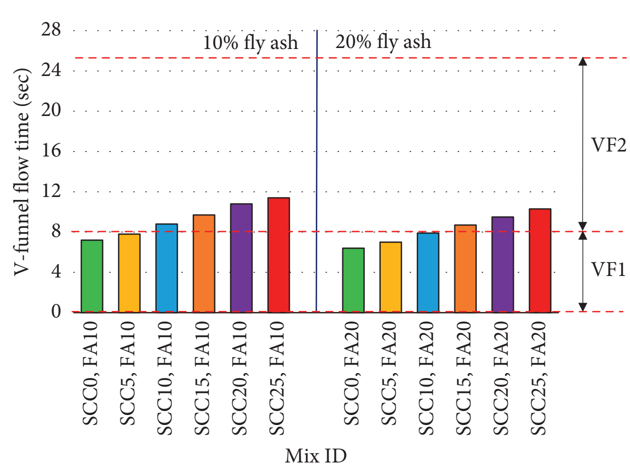

FIGURE 3: V-funnel test values for the fresh concrete.

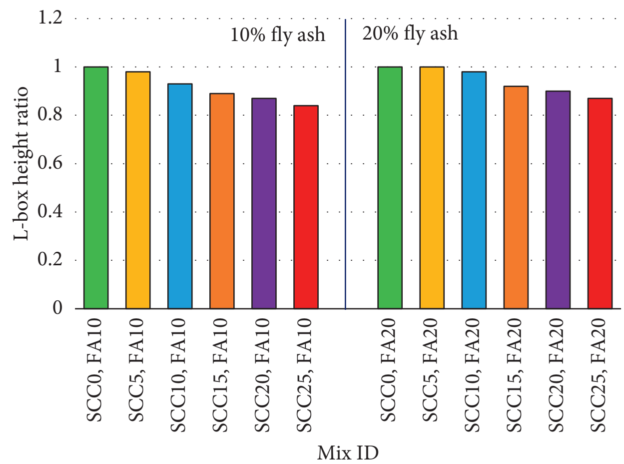

Figure 4: L-box ratio test values for the fresh concrete.

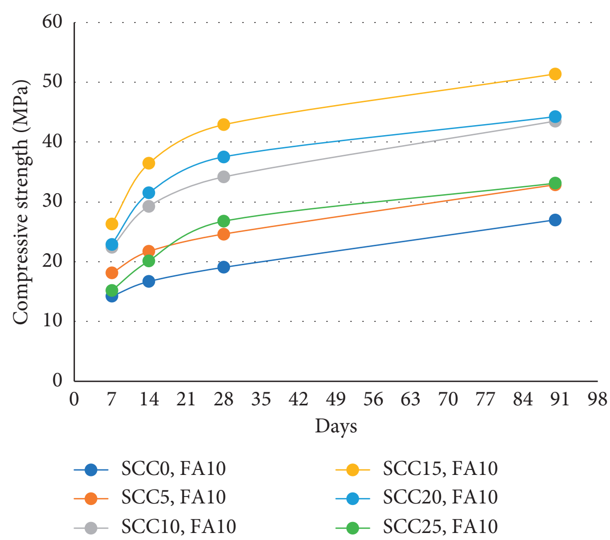

Figure 5: Compressive strength test results for concrete mixes with 10% replacement of fly ash.

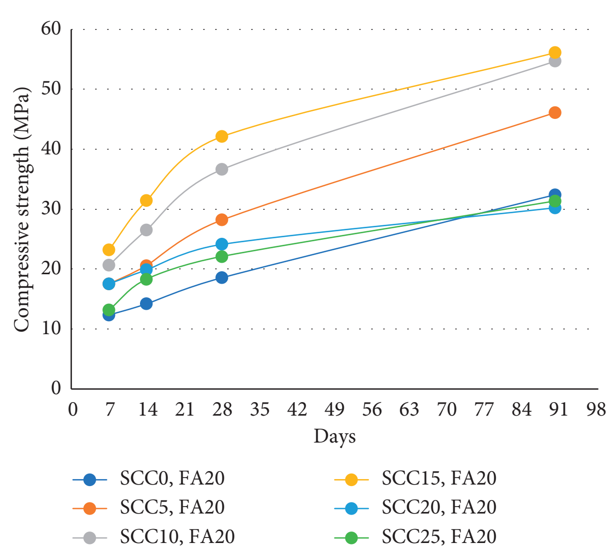

Figure 6: Compressive strength test results for concrete mixes with 20% replacement of fly ash.

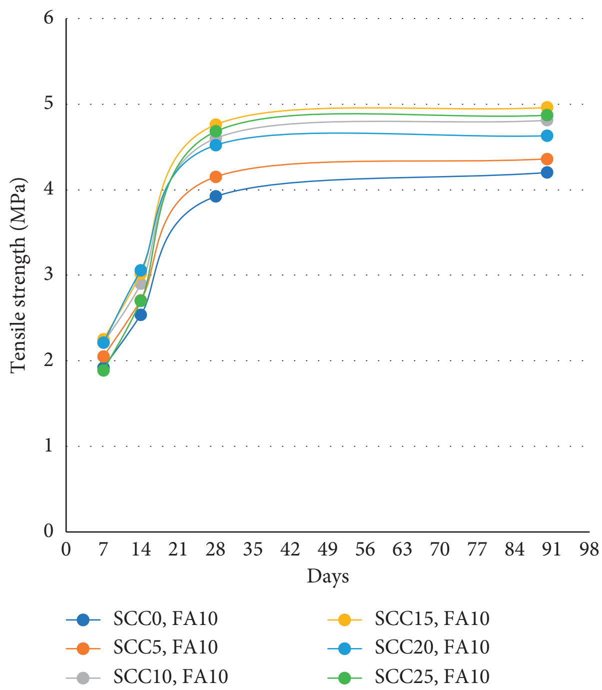

FIGURE 7: Tensile strength test results for concrete mixes with 10% replacement of fly ash.

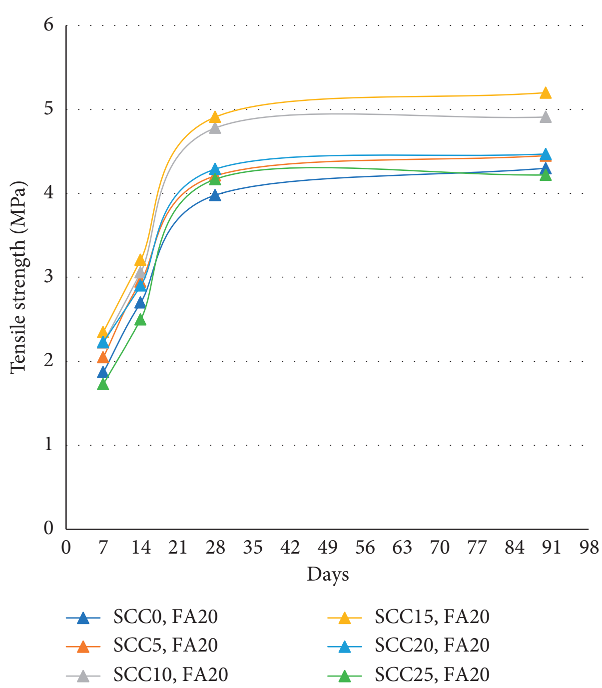

FIGURE 8: Tensile strength test results for concrete mixes with 20% replacement of fly ash.

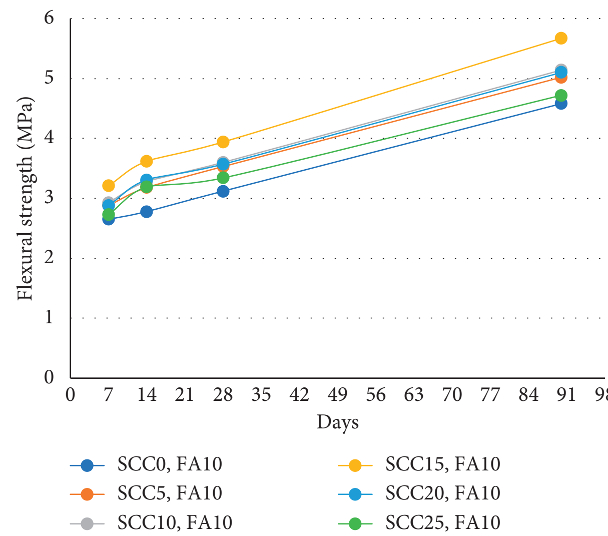

FIGURE 9: Flexural strength test results for concrete mixes with 10% replacement of fly ash.

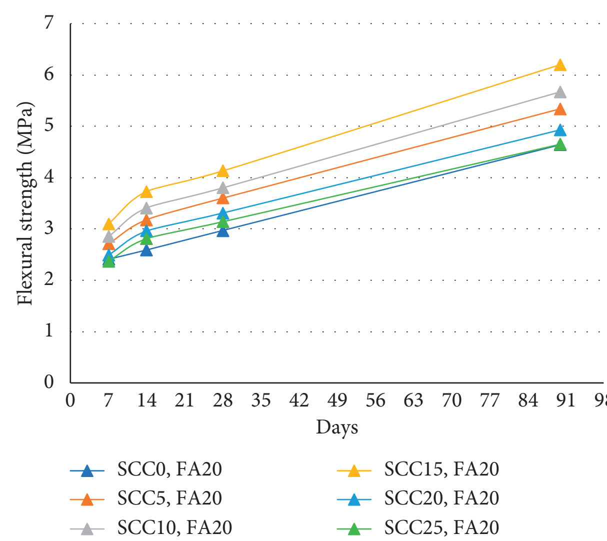

FIGURE 10: Flexural strength test results for concrete mixes with 20% replacement of fly ash.

was noted to have 14.95% lesser strength than the design strength owing to the absence of UFNSP and presence of fly ash which do not promote early age strength in the concrete. On the other hand, when 20% of the weight of fly ash was added to the concrete mix, the attained strength was 30.62%, 85.82%, 120.35%, 126.11%, 21.84%, and 26.43% more than the design strength for SCC0FA20, SCC5FA20, SCC10FA20, SCC15FA20, SCC20FA20, and SCC25FA20, respectively. The strength attained was noted to increase gradually from 7 days to 28 days, whereas a steep rise was noted at 90 days particularly for SCC15FA20 in which 126.11% rise was noted in the compressive strength of the specimens. A rapid gain of compressive strength was visibly noted in the later age (90 days) of the concrete when compared with the early age (7 days) of 162.72%, 163.24%, 165.10%, 142.00%, 72.50%, and 138.09% for SCC0FA20, SCC5FA20, SCC10FA20, SCC15FA20, SCC20FA20, and SCC25FA20, respectively. The concrete specimens of SCC10FA20 were noted to exhibit higher compressive strength of 165.10% when compared with the early days than any other concrete mixes developed in this study. In cases of the mixes with 20% of fly ash and various percentages of

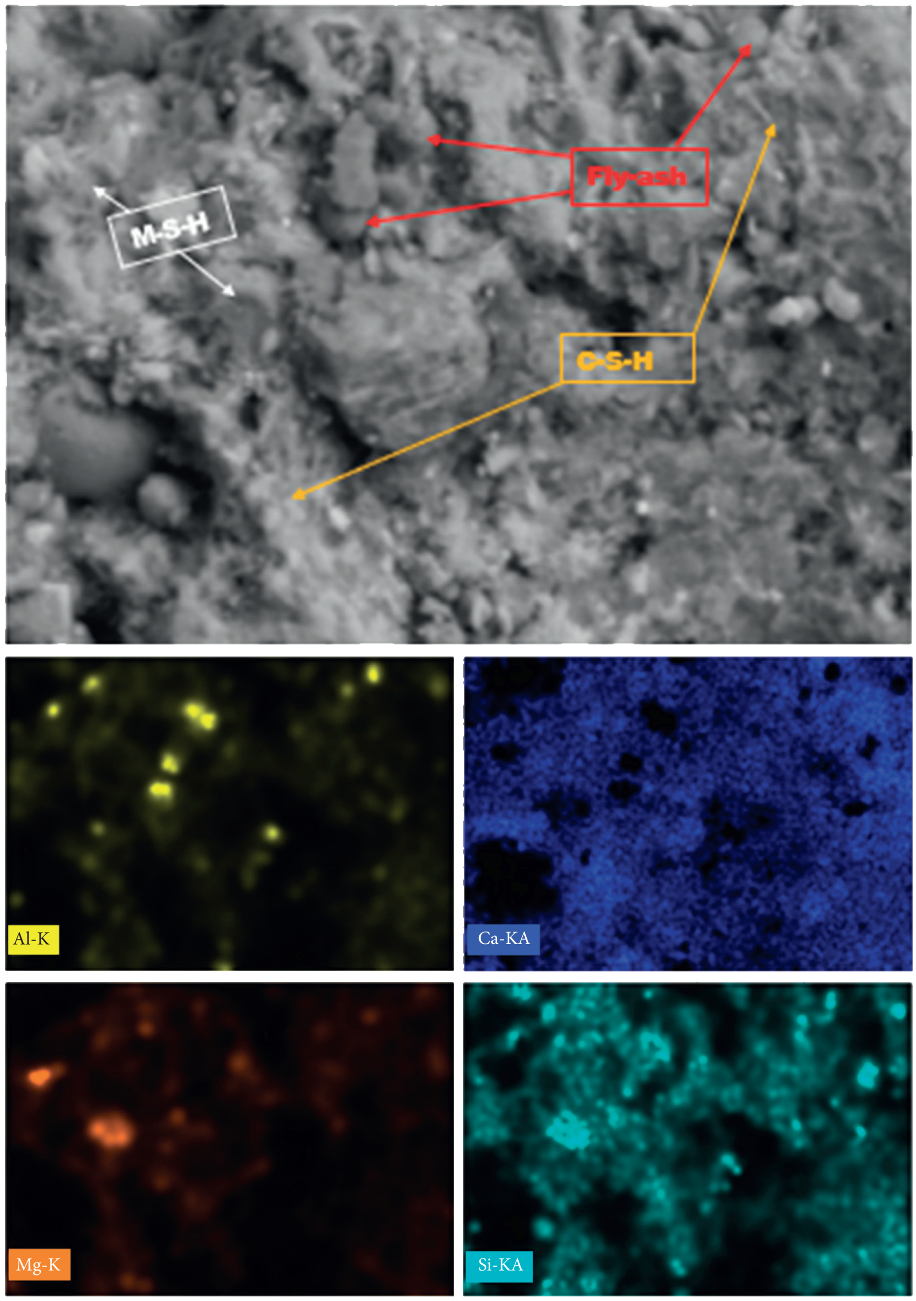

FIGURE 11: SEM image and corresponding EDX mapping for Al, Ca, Mg, and Si in SCC5FA10.

UFNSP, the SCC0FA20 mixes were noted to develop 17.18% lower compressive strength than the designed strength owing to the later age strength development of the fly ash and the absence of the UFNSP. Also, for the SCC25FA20 mix, the compressive strength was found to be 1.92% lower than the design strength since 45% of the cement was replaced by fly ash and UFNSP which lowers the pozzolanic reaction.

The presence of the C-S-H gel and M-S-H gel was liable for the strength gain [37] in the concrete specimens by intruding into the cement matrix owing to the finer particle size of the UFNSP. In spite of the rise in the concrete strength, the infirmity in the flowability of the concrete is vanquished by the addition of fly ash in the concrete specimens which in turn improves the workability as well as the later age strength due to the pozzolanic reaction [38, 39].

4.2.2. Tensile Strength. The test results for the tensile strength of the hardened concrete are presented in Figures 7 and 8. The attained strength was 1.75% lower than the designed strength for the SCCFA10 mix owing to the later age strength attainment of fly ash and the absence of the UFNSP in the mix, whereas, for SCC5FA10, SCC10FA10, SCC15FA10, SCC20FA10, and SCC25FA10, the tensile strength was 4.01%, 15.29%, 19.30%, 13.28%, and 17.29% higher than the design strength, respectively.

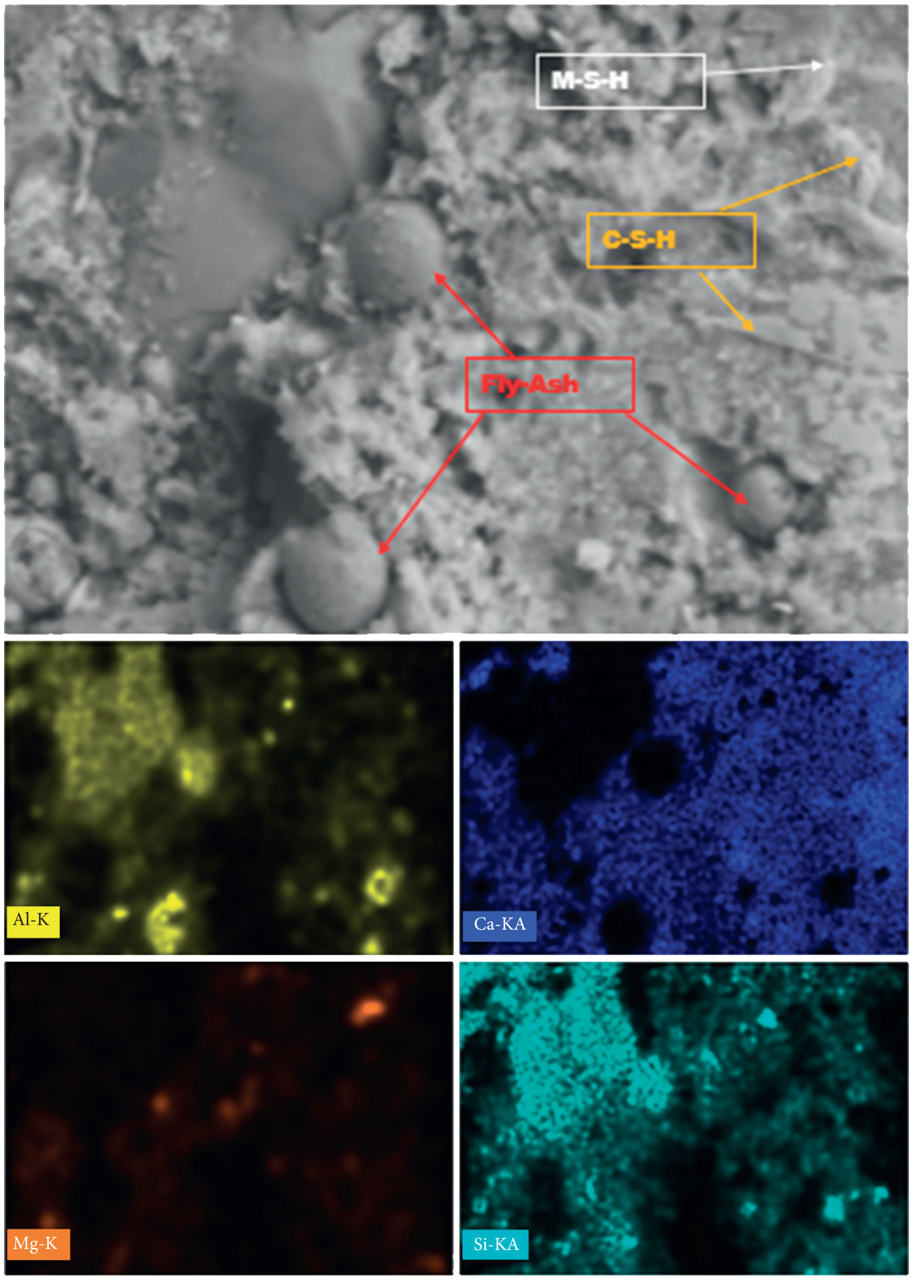

FIGURE 12: SEM and corresponding EDX mapping for Al, Ca, Mg, and Si in SCC5FA20.

The maximum tensile strength gain at 90 days was noted for SCC15FA10 up to 19.52% more than the control specimens, whereas the same was increased up to 25.30% for SCCFA20 denoting the gain in compressive strength upon the addition of fly ash content in the mix.

4.2.3. Flexural Strength. The values of the flexural strength obtained in the hardened concrete are plotted in Figures 9 and 10. The attained strength was 1.26% lower than the designed strength signifying the rise in the flexural strength up to 15% of replacement of UFNSP with 10% of fly ash in the mix, whereas, for the SCC0FA20 and SCC25FA20 mixes, 6.03% and 0.63% fall is noted due to the lower steatite content and higher steatite content, respectively. A maximum of 37.17% rise is noted in SCC15FA20 mix at 90 days owing to the later age strength attainment of fly ash.

5. Microstructural Analysis and Elemental Mapping

The samples developed for this study were analyzed with scanning electron microscope (SEM) and elemental EDX

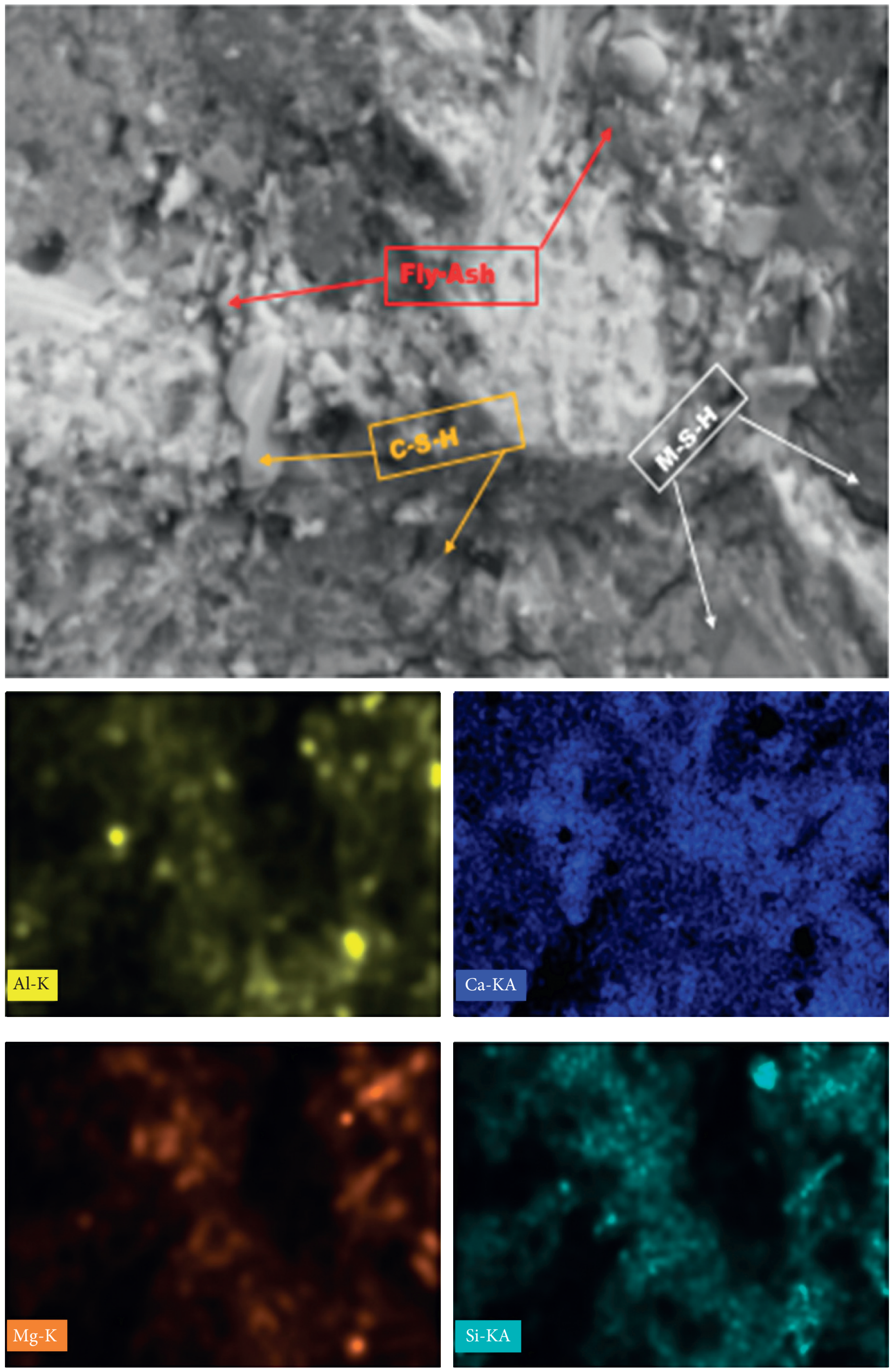

FIGURE 13: SEM image and corresponding EDX mapping for Al, Ca, Mg, and Si in SCC15FA10.

mapping at 28 days to validate the positive behaviour of concrete with the addition of UFNSP and fly ash. The images of the microstructure and the elemental EDX mapping are plotted (Figures 11to 16) to perceive the out turn upon the introduction of the UFNSP and fly ash in the concrete composite depicts the absence of magnesium segments in the control specimen and presence of calcium silicate hydrates. In SCC5FA10 and SCC5FA20,

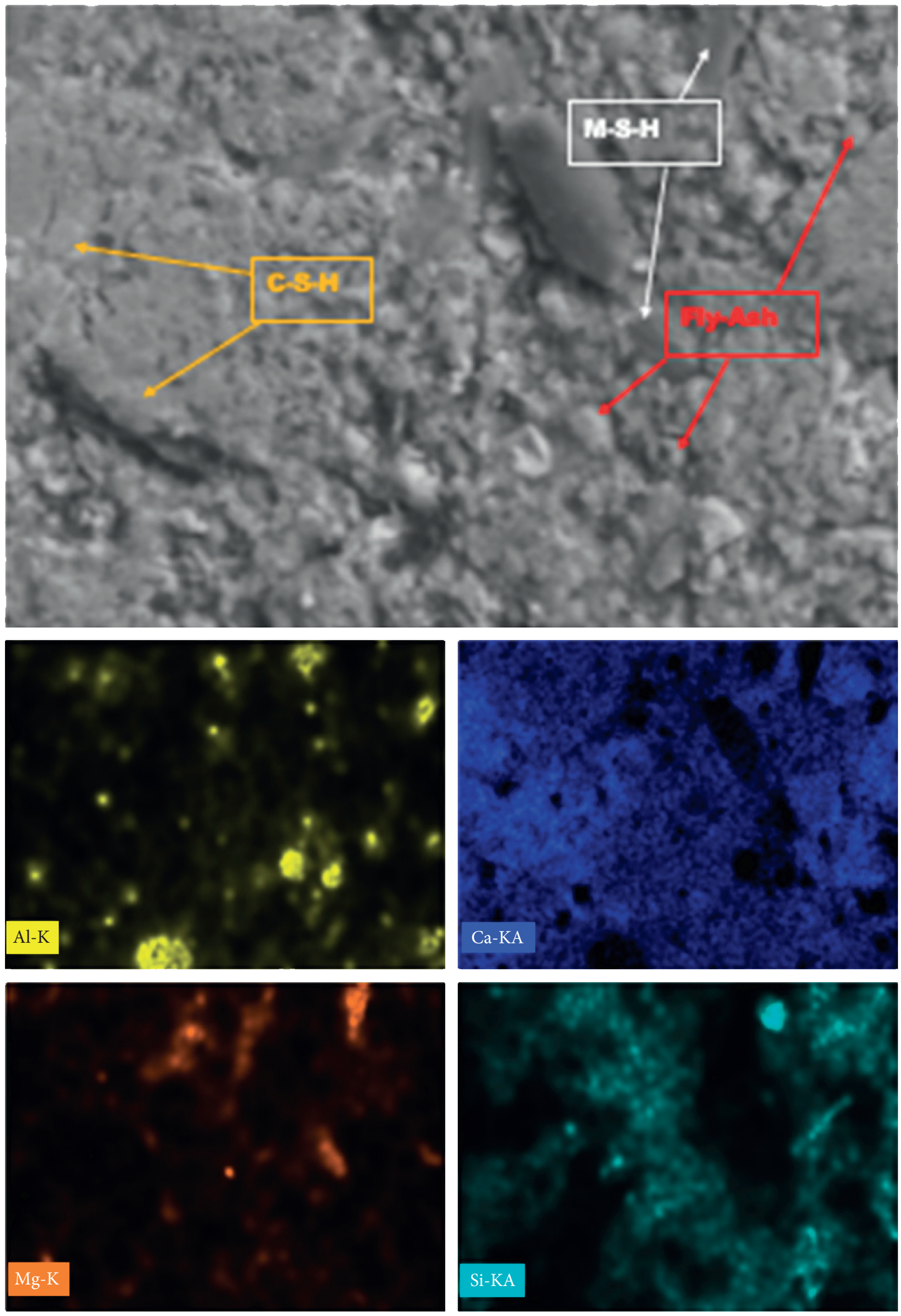

FIGURE 14: SEM image and corresponding EDX mapping for Al, Ca, Mg, and Si in SCC15FA20.

elements of C-S-H as well as M-S-H were noted out, of which the M-S-H gel was very limited when compared with the C-S-H owing to the minimal replacement levels of UFNSP.

Traces of fly ash particles were also noted in SCC5FA10 and SCC5FA20 which tends to act as a filler component thus minimizing the internal voids which in turn dense [40] and improves the strength parameters. The traces of M-S-H were

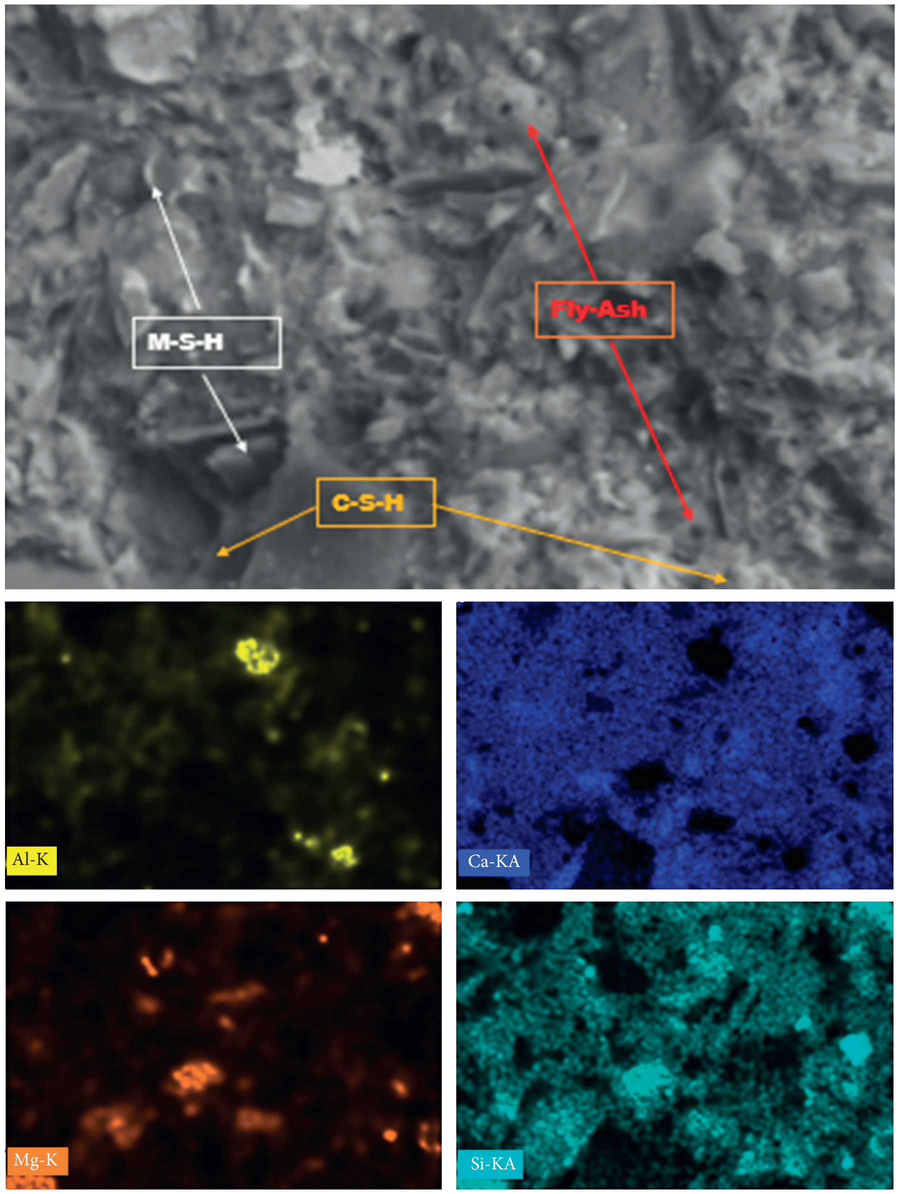

Figure 15: SEM image and corresponding EDX mapping for Al, Ca, Mg, and Si in SCC25FA10.

noted to significantly increase with the replacement level of UFNSP. For the sample specimens of SCC15FA10 and SCC15FA20, the traces of M-S-H are denser and outstanding owing to the solidification of the M-S-H and development of free calcium elements leading to the breakpoint of the gain in strength [31]. Further in samples of SCC20FA10, SCC20FA20, SCC25FA10, and SCC25FA20, breakdown of the magnesium silicates was observed which leads to the reduction of the strength. Thus, both the calcium and the magnesium silicates are liable for the gain in the mechanical strength of the samples. Also, the rise in the crystalline nature of the M-S-H causes the SCC20FA10, SCC20FA20, SCC25FA10, and SCC25FA20 samples to reduce the strength gain after the breakpoint [41], whereas the fly ash traces were noted to act as a filling material throughout all the samples, thus enhancing the harden properties.

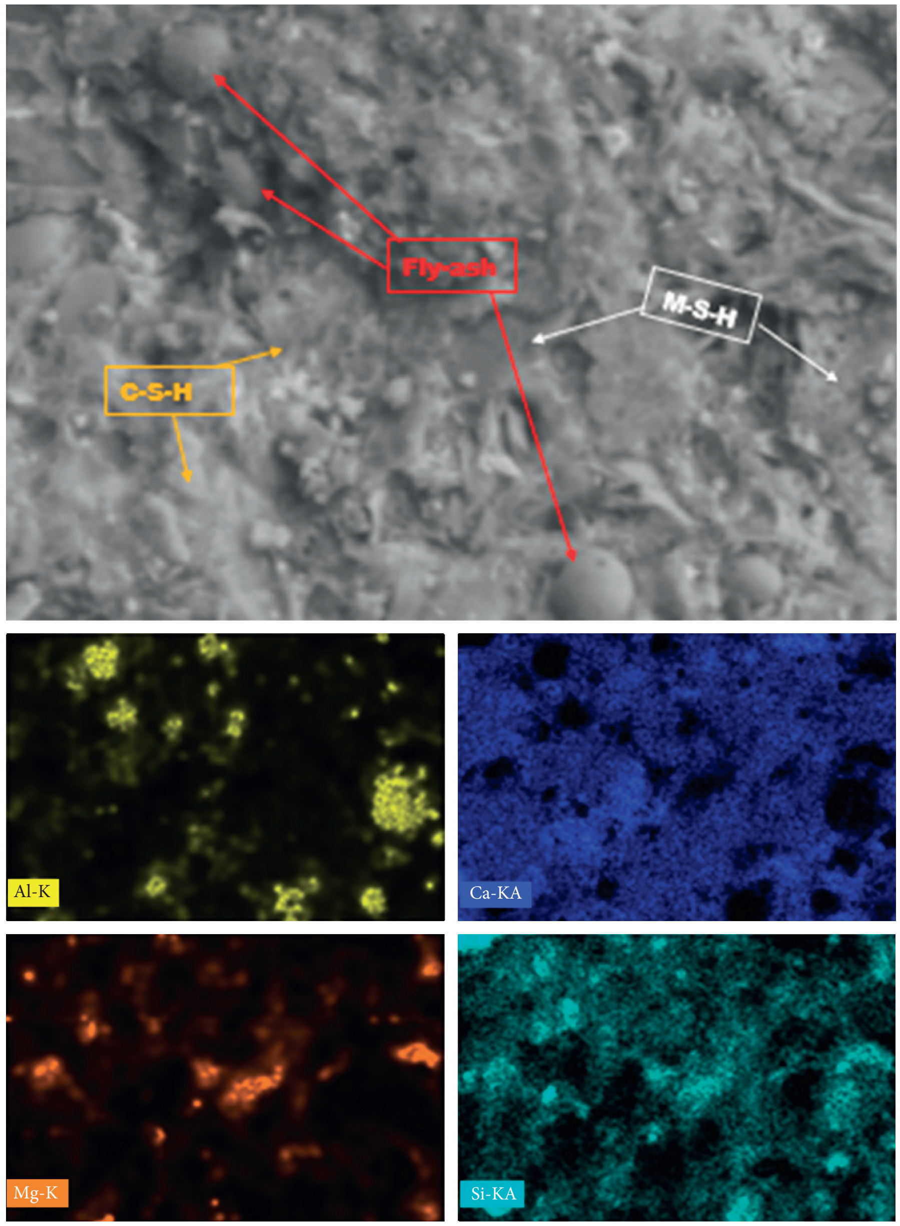

FIGURE 16: SEM image and corresponding EDX mapping for Al, Ca, Mg, and Si in SCC25FA20.

6. Conclusions

In reference to the findings in the present study, the following conclusions were drawn:

(i) The UFNSP in the SCC reduces the flow properties but the reduction in the flow is compensated by addition of fly ash in the mix.

(ii) Test results showcase the optimum slump values between 645 mm and 760 mm. It is clear that addition of steatite minimizes the flow properties whereas in contrast the introduction of fly ash overdoes the same. Maximum slump values were registered at SCC0FA20 which is categorized as SF3 whereas all the remaining mixes were classified as SF2 except SCC25FA10 which exhibits the lowest slump value and was categorized as SF1 as per the European guidelines for self-compacting concrete.

(iii) In T_{500} and V-funnel test, better viscosity is obtained for the mixes with higher replacement of fly ash and low quantity of steatite. In T_{500} slump flow test, except SCC0FA20 which is in VS1, all the other mixes were classified as VS2.

(iv) In V-funnel test, SCC0FA10, SCC5FA10, SCC0FA20, SCC5FA20, and SCC10FA20 were categorized under VF1, whereas all the other mixes with higher amount of UFNSP were categorized under VF2.

(v) Based on the results obtained from the L-box test, ideal fluidity is obtained for SCC0FA10, SCC0FA20, and SCC5FA20 whereas higher replacement of steatite retards the fluidity of the mix.

(vi) The harden properties (compressive strength, tensile strength, and flexural strength) were noted to improve by the addition of steatite up to 15%, beyond which there is a fall. The reason for increase in the strength is that till 15% addition of steatite the voids present in the control specimen was filled by steatite beyond which the additional steatite content became residual steatite which does not serve as a filling material anymore. Hence, the strength started getting reduced. Optimum compressive strength, tensile strength, and flexural strength were achieved for the mix SCC15FA20 at 90 days owing to the denser solidification of the M-S-H gel.

(vii) When the steatite is added to the concrete mixture, there is a possibility of formation of MgO. The MgO formed has the property of uneven expansion beyond the optimum percentage (i.e., 15%); such an uneven expansion resulted in the microcracks which in turn reduced the strength of the concrete. The same was reflected in the EDX elemental analysis also. The quantity of Mg increased with the increase in the addition of steatite. Up to 15% the MgO expansion was compensated by the void spaces, beyond which the expansion created a stress inside the concrete leading to microcracks, thereby reducing the strength. Also, addition of steatite beyond a particular limit reduces the cement content percentage; hence, it reduces the strength. So, it is advised not to use the steatite beyond 25% which may reduce the strength more than the control specimen.

Thus, steatite being a naturally available source as an apt filling material in the production of SCC which procures the peerless test results when combined with Fly ash can be an ideal choice in the new construction era. This advancement can save a lot of time along with the better enhancement of the concrete structure with no compromise in the strength and durability of the same. This technique in turn minimizes the emission of the CO_2 emission, enables the usage of naturally available sources, productive usage of the byproducts (Fly ash), and also minimizes the manpower (SCC). Further studies can be conducted to analyze the behavior of thus developed SCC under variant temperatures and adverse environmental conditions which enables the usage of the same in larger scale in the construction Industry.

Data Availability

The data that support the findings of this study are available within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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